

Cold Dark Matter Isocurvatures Perturbations: Cosmological Constraints and Applications

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In this paper we present the constraints on cold dark matter (CDM) isocurvature contributions to the cosmological perturbations. By employing Markov Chain Monte Carlo method (MCMC), we perform a global analysis for cosmological parameters using the latest astronomical data, such as 7-year Wilkinson Microwave Anisotropy Probe (WMAP7) observations, matter power spectrum from the Sloan Digital Sky Survey (SDSS) luminous red galaxies (LRG), and “Union2” type Ia Supernovae (SNIa) sample. We find that the correlated mixture of adiabatic and isocurvature modes are mildly better fitting to the current data than the pure adiabatic ones, with the minimal χ^2 given by the likelihood analysis being reduced by 3.5. We also obtain a tight limit on the fraction of the CDM isocurvature contributions, which should be less than 14.6% at 95% confidence level. With the presence of the isocurvature modes, the adiabatic spectral index becomes slightly bigger, $n_s^{\text{adi}} = 0.972 \pm 0.014$ (1σ), and the tilt for isocurvature spectrum could be large, namely, the best fit value is $n_s^{\text{iso}} = 3.020$. Finally, we discuss the effect on WMAP normalization priors, shift parameter R , acoustic scale l_A and z_* , from the CDM isocurvature perturbation. By fitting the mixed initial condition to the combined data, we find the mean values of R , l_A and z_* can be changed about 2.9σ , 2.8σ and 1.5σ respectively, comparing with those obtained in the pure adiabatic condition.

I. INTRODUCTION

The accumulation of WMAP seven year measurement on cosmic microwave background radiation (CMB) [1], associated with observations of SDSS [2], provide wealthy information on the anisotropies and inhomogeneities of our universe, in light of which the perturbation theory has been tested in certain level. Currently, various observational data favor the simplest concordance cosmological model, which has six free parameters and the pure adiabatic initial condition [1, 3–6]. Although the concordance model fits the data quite well, it is always worthy to consider alternative candidates. Namely, it is important to study observational constraints on initial states of cosmological perturbations at reheating surface.

Generically, there exists two classes of modes of cosmological perturbations, with one being adiabatic of which the trajectory is parallel to the background evolution, while the other isocurvature of which the trajectory is orthogonal to the background evolution[7–15]. However, a first lesson from observational data is that the primordial fluctuations are nearly adiabatic; additionally, an isocurvature mode is also expected to be negligible as is predicted by the simplest inflation model in terms of a single inflaton field and a rapidly reheating process[16]. Therefore, one usually makes the data fitting without considering the isocurvature mode.

Accompanied with developments of inflationary cosmology, models of multiple field inflation were extensively studied in the literature[17–27], which predicted an existence of primordial isocurvature fluctuations. These primordial isocurvature modes could be transferred into cosmological perturbations after reheating, such as Bayon, CDM, DE, and neutrino respectively[28–31]. Consequently, the attention on isocurvature modes has been awoken in recent years[32, 33].

One may notice that, although the pure isocurvature primordial perturbation has been ruled out by the Boomerang and MAXIMA-1 data [34] already, a mixture of adiabatic and isocurvature modes can be in agreement with the current data fortunately. In the literature [35–46], the studies on constraining the isocurvature fluctuation have been performed extensively using various observational data, such as CMB, LSS, integrated Sachs-Wolfe effect or Lyman- α forest data. With the WMAP7 data, the totally un-correlated and anti-correlated adiabatic, non-adiabatic perturbations are constrained [1], which are performed by fixing the correlation coefficients to be 0 or -1 , respectively.

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In this paper, we study the constraints on the isocurvature modes of cosmological perturbations in light of the latest observational data. We consider a generic scenario that the adiabatic modes and isocurvature ones are allowed mixed through a correlation matrix which could be arising from a time-varying background trajectory. In the detailed analysis, we treat the coefficients of correlation matrix as free parameter and make the data fitting. Comparing with the previous results in the literature, our result shows a slight improvement on the final constraints of the mixed initial condition parameters. Namely, CDM isocurvature components are stringently limited, the contribution from the isocurvature modes are only allowed in small scales, also the error bars of initial condition parameters become smaller than the past works in the literature, which can be observed from the one dimensional probability distribution of the fraction parameter α as analyzed in the main context.

The WAMP normalization priors, R , l_A and z_* encoding the information of background cosmic distances, can be applied to greatly simplify the numerical calculations of determining cosmological parameters, such as the EoS of dark energy. It was found that these priors could be sensitive to the peak locations and local structures of the CMB temperature power spectrum [47]. However, it is well-known that these quantities can be affected by CDM isocurvature perturbation. Therefore, we study the effects on the WMAP normalization priors given by the WMAP group from the isocurvature mode perturbation.

The outline of this paper is as follows. In Section II, we describe the parametrization of cosmological perturbations with adiabatic and isocurvature modes mixed, and then we consider a specific example to illustrate the effects of isocurvature perturbation imprinted on the CMB temperature power spectrum and LSS matter power spectrum respectively. In Section III, we perform a global analysis and introduce the data we applied and the parameters used in the data fitting. The constraints on these parameters are present in detail in Section IV, and the corresponding effects on reduced distance parameters are discussed. Finally, Section V includes the conclusions and discussion.

II. PARAMETRIZATION OF CORRELATED ADIABATIC AND ISOCURVATURE PERTURBATIONS

For model-independent consideration, the initial conditions for the correlated mixture of adiabatic and isocurvature modes can be written as

$$\mathcal{P}^{ij} = A_s^{ij} \left(\frac{k}{k_0} \right)^{n_s^{ij}-1}, \quad (1)$$

where k_0 is the pivot scale. Here, A_s^{ij} and n_s^{ij} are 2×2 symmetric matrices which characterize the amplitude and power spectrum index, respectively. We have

$$A_s^{ij} = \begin{pmatrix} A_s^{\text{adi}} & \sqrt{A_s^{\text{adi}} A_s^{\text{iso}}} \cos \Delta \\ \sqrt{A_s^{\text{adi}} A_s^{\text{iso}}} \cos \Delta & A_s^{\text{iso}} \end{pmatrix}, \quad (2)$$

where $\cos \Delta = A_s^{\text{adi,iso}} / \sqrt{A_s^{\text{adi}} A_s^{\text{iso}}}$ describes the correlation between the adiabatic mode and the isocurvature mode [20], A_s^{adi} and A_s^{iso} are the amplitude of adiabatic and isocurvature modes, respectively. The index matrix n_s^{ij} is given by:

$$n_s^{ij} = \begin{pmatrix} n_s^{\text{adi}} & n_s^{\text{cor}} \\ n_s^{\text{cor}} & n_s^{\text{iso}} \end{pmatrix}, \quad (3)$$

where n_s^{adi} and n_s^{iso} are the spectrum indices for adiabatic and isocurvature modes. Following Ref. [39], we assume $n_s^{\text{cor}} = (n_s^{\text{adi}} + n_s^{\text{iso}})/2$ for simplicity.

Both adiabatic and isocurvature perturbations seed the structure formation of our universe, and can be imprinted in CMB temperature, polarization power spectrum, as well as matter power spectrum of galaxies surveys. Symbolically, the anisotropies of CMB photons can be written as

$$\frac{\delta T}{T} = \left(\frac{\delta T}{T} \right)_{\text{adi}} + \left(\frac{\delta T}{T} \right)_{\text{iso}} + \left(\frac{\delta T}{T} \right)_{\text{corr}}. \quad (4)$$

Consequently, the CMB power spectrum is given by

$$C_\ell^{\text{TT}} = A_s^{\text{adi}} \hat{C}_\ell^{\text{adi}} + A_s^{\text{iso}} \hat{C}_\ell^{\text{iso}} + 2\sqrt{A_s^{\text{adi}} A_s^{\text{iso}}} \hat{C}_\ell^{\text{adi,iso}} \cos \Delta, \quad (5)$$

where initial power spectrum can be obtained as follows,

$$\hat{C}_\ell^{ij} = \frac{4\pi}{2\ell+1} \int d \ln k \left(\frac{k}{k_0} \right)^{n_s^{ij}-1} \Theta_\ell^i(k) \Theta_\ell^j(k), \quad (6)$$

with i, j standing for adiabatic or isocurvature and Θ_ℓ^x are the transfer functions of the radiation at initial moment. There are similar formulas for CMB polarization power spectra C_ℓ^{EE} , C_ℓ^{BB} and temperature-polarization cross correlation power spectrum C_ℓ^{TE} .

Moreover, the matter power spectrum $P(k)$ can be written as:

$$P(k) = A_s^{\text{adi}} \hat{P}^{\text{adi}}(k) + A_s^{\text{iso}} \hat{P}^{\text{iso}}(k) + 2\sqrt{A_s^{\text{adi}} A_s^{\text{iso}}} \hat{P}^{\text{adi,iso}}(k) \cos \Delta, \quad (7)$$

with

$$\hat{P}^{\text{ij}}(k) = \left(\frac{k}{k_0}\right)^{n_s^{\text{ij}}-1} T^{\text{i}}(k) T^{\text{j}}(k), \quad (8)$$

where $T^x(k)$ are the transfer functions of matter component at initial moment.

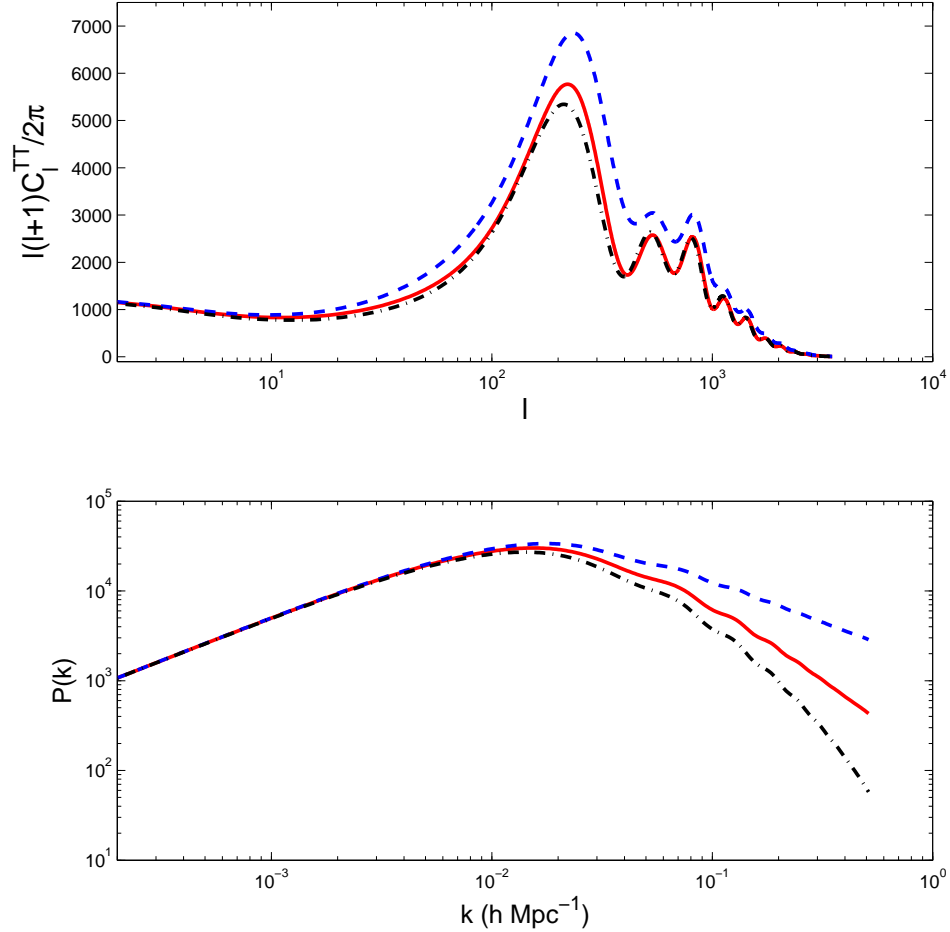


FIG. 1: The CMB temperature power spectra and LSS matter power spectra are plotted using different initial conditions in the upper and lower panels, respectively. The red solid lines are given by the best fit model with the mixed initial condition. The blue dash lines and the black dash-dot lines are given by choosing $A_s^{\text{iso}} = 1 \times 10^{-10}$ and $\cos \Delta = -1$, respectively.

In order to show the effect of isocurvature perturbations, in Fig.1 we plot the CMB temperature power spectra (upper panels) and LSS matter power spectra (lower panel). The red solid lines are given by the best fit model with mixed initial conditions by fitting the current observational data: $\omega_b = 0.0226$, $\omega_c = 0.1144$, $A_s^{\text{adi}} = 2.407 \times 10^{-9}$, $A_s^{\text{iso}} = 3.885 \times 10^{-12}$, $n_s^{\text{adi}} = 0.968$, $n_s^{\text{iso}} = 3.020$, $\cos \Delta = 0.149$. The blue dash line and black dash-dot lines are given by choosing $A_s^{\text{iso}} = 1 \times 10^{-10}$ and $\cos \Delta = -1$ instead, respectively. One can see that by taking into account the CDM isocurvature modes and its correlation with adiabatic perturbations, the height and location of the peaks of TT spectra will be modified, and the amplitude of matter power spectrum on small scales are changed significantly.

III. OBSERVATIONAL CONSTRAINTS

A. Data

We perform a global analysis by employing a modified MCMC package CosmoMC¹ [48], in which we have made an extension of the initial perturbations by including correlated adiabatic and CDM isocurvature modes. In computation of CMB we have included the WMAP7 temperature and polarization power spectra with the routine for computing the likelihood supplied by the WMAP team². Since the CDM isocurvature perturbations affect the power spectrum on small scales, we also include some small-scale temperature anisotropies measurements, ACBAR [49], CBI [50] and Boomerang [51]. Furthermore, we use the matter power spectrum measured by the observations of luminous red galaxies (LRG) from SDSS data release seven [2], and the “Union II” supernovae datasets calibrated by SALT2 template [52].

B. Parameters

As pointed out in Refs.[39, 44], the constraints of the spectral index may depend on the pivot scale. In order to avoid such dependence, we do not take the spectra indices n_s^{ij} as free parameters in our analysis. We take two different amplitudes $A_s(k_1)$ and $A_s(k_2)$ at two pivot scales $k_1 = 0.002$ and $k_2 = 0.05$ to be free. And the spectra indices can be derived by

$$n_s^{\text{ij}} - 1 \equiv \frac{\ln[\mathcal{P}^{\text{ij}}(k_2)/\mathcal{P}^{\text{ij}}(k_1)]}{\ln[k_2/k_1]} = \frac{\ln[A_s^{\text{ij}}(k_2)/A_s^{\text{ij}}(k_1)]}{\ln[k_2/k_1]}. \quad (9)$$

We assume that the overall amplitude is composed of two components:

$$A_s \equiv A_s^{\text{adi}} + A_s^{\text{iso}}, \quad (10)$$

and the fraction of adiabatic part is defined by

$$\alpha \equiv A_s^{\text{adi}}/A_s. \quad (11)$$

Thus, our most general parameter space is

$$\mathbf{P} \equiv \{\omega_b, \omega_c, \Theta_s, \tau, \cos \Delta, \alpha_1, \alpha_2, A_s(k_1), A_s(k_2)\}. \quad (12)$$

where $\omega_b \equiv \Omega_b h^2$, $\omega_c \equiv \Omega_c h^2$ denotes physical baryon density and cold dark matter density relative to critical density respectively; $\Theta_s \equiv 100 \frac{r_s}{d_A}$ is the ratio of sound horizon to angular diameter distance at decoupling, τ characterizes the optical depth to reionization. $A_s(k_1)$, $A_s(k_2)$, α_1 and α_2 are the amplitudes and the fractions of adiabatic mode at two scales, respectively. In our calculation, we assume the flat universe and dark energy is the cosmological constant.

TABLE I: The mean values and 1σ errors of A_s given by EQ. 10 at two different pivot scale, α_2 and $\cos \Delta$, while the limit of α_1 is for 95% confidence level.

$\log[10^{10} A_s(k_1)]$	$\log[10^{10} A_s(k_2)]$	α_1	α_2	$\cos \Delta$
$3.185^{+0.041}_{-0.042}$	$3.622^{+0.242}_{-0.247}$	$> 93.9\%$	$0.594^{+0.056}_{-0.083}$	$0.094^{+0.075}_{-0.095}$

TABLE II: The mean values and 1σ errors of the parameters related to the mixed initial adiabatic and CDM isocurvature perturbations.

	$\log[10^{10} A_s^{\text{adi}}]$	n_s^{adi}	$\log[10^{10} A_s^{\text{iso}}]$	n_s^{iso}	$\cos \Delta$	χ^2_{min}
Adiabatic	3.204 ± 0.036	0.964 ± 0.010	—	—	—	8217.0
Mixed	3.165 ± 0.044	0.972 ± 0.014	$-1.375^{+1.233}_{-1.306}$	$2.246^{+0.494}_{-0.428}$	$0.094^{+0.075}_{-0.095}$	8213.5

¹ <http://cosmologist.info/cosmomc/>.

² <http://lambda.gsfc.nasa.gov/>.

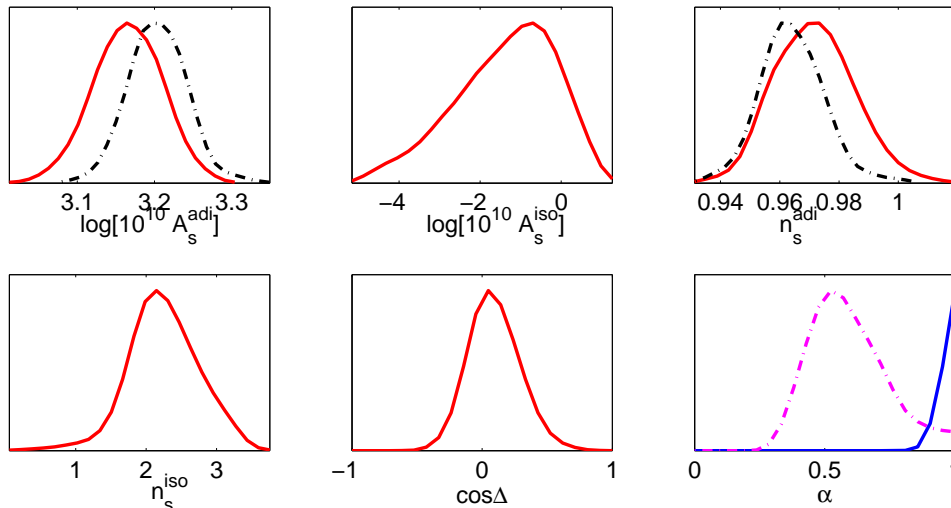


FIG. 2: One dimensional probability distributions of initial conditions associated parameters are plotted with red solid lines. For $\log[10^{10} A_s^{\text{adi}}]$ and n_s^{adi} , we specially make a comparison with the results obtained from the pure adiabatic initial conditions which are plotted with black dash lines. We also plot the adiabatic perturbation modes fraction parameter α_1 and α_2 using the purple dash-dot line and blue solid line, respectively.

IV. GLOBAL FITTING RESULTS

In this section, we present the main constraints on the cosmological parameters, as well as the parameters related to the CDM isocurvature perturbations. Then, we discuss the effects on the WMAP normalization priors when taking into account CDM isocurvature perturbations.

A. Constraints on cosmological parameters

In table I and table II we list the constraints on the initial condition associated parameters by fitting the latest observational data. The parameters presented in table I are the free parameters during our calculation, while those in table II are the derived parameters from the those in table I according to EQ. (9-11), and both results are given by the statistics of the samples given by our MCMC approach. From the mixed initial conditions, the constraints on the adiabatic perturbation are $\log[10^{10} A_s^{\text{adi}}] = 3.165 \pm 0.044$ and $n_s^{\text{adi}} = 0.972 \pm 0.014$ at 68% confidence level. The adiabatic spectrum index becomes larger, when comparing with the constraint $n_s^{\text{adi}} = 0.964 \pm 0.010$ (1σ) from the pure adiabatic initial condition. For the CDM isocurvature mode, the constraints are $\log[10^{10} A_s^{\text{iso}}] = -1.375^{+1.233}_{-1.306}$ and $n_s^{\text{iso}} = 2.246^{+0.494}_{-0.428}$ (68% C.L.). Furthermore, the coefficient of the correlation is limited as $-0.113 < \cos \Delta < 0.473$ at 95% C.L.. Comparing with the minimal χ^2 of these two cases, we find that a weakly positive-correlated mixture of CDM isocurvature and adiabatic perturbations is mildly favored by the current data. However, the fraction of CDM isocurvature mode can not be larger than 14.9% at 95% confidence level. The constraining power mainly comes from WMAP7 temperature and polarization power spectra, since too large fraction of the CDM isocurvature mode will lead to the overstated modification of the shape of acoustic peaks in TT and TE power spectra, as illustrated in Fig.1. Our results are consistent with the previous results reported in Ref.[44].

In Fig.2, we plot one dimensional posterior probability distributions of A_s^{adi} , A_s^{iso} , n_s^{adi} and n_s^{iso} , as well as $\cos \Delta$ and α at the two different pivot scales. In Fig.3 we also plot the one dimensional probability distributions of the other cosmological parameters obtained from the mixed initial conditions and pure adiabatic condition cases. The red solid lines are given by the mixed initial conditions, while the black dash lines are from the pure adiabatic one. One can see that with the mixed initial conditions, the results favor a slightly smaller ω_m and larger θ due to the correlation of the CDM isocurvature perturbations with other cosmological parameters when considering the non-adiabatic initial condition in our analysis.

We find that there exist apparent correlations among the parameters related to initial conditions and other background cosmological parameters, as illustrated in Fig. 4. The coefficient $\cos \Delta$ is correlated with Ω_m , since a positive

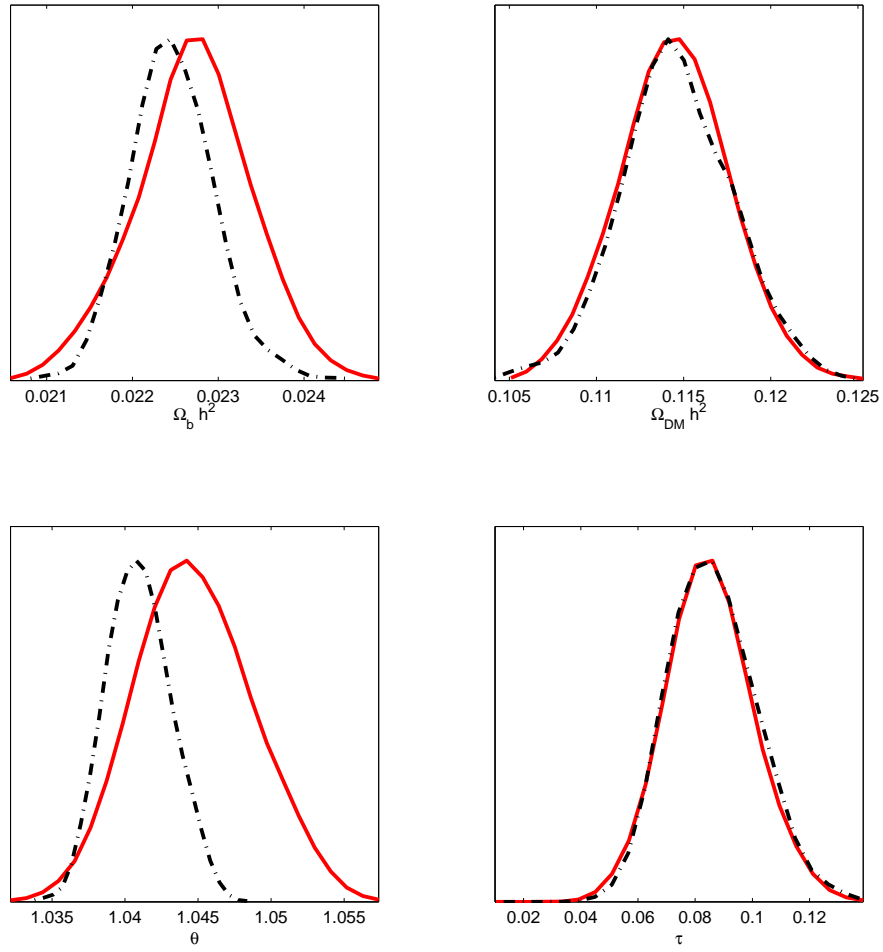


FIG. 3: One dimensional probability distributions of some background cosmological parameters, the red solid lines are given by the mixed initial condition, while the black dash-dot lines are from the pure adiabatic conditions.

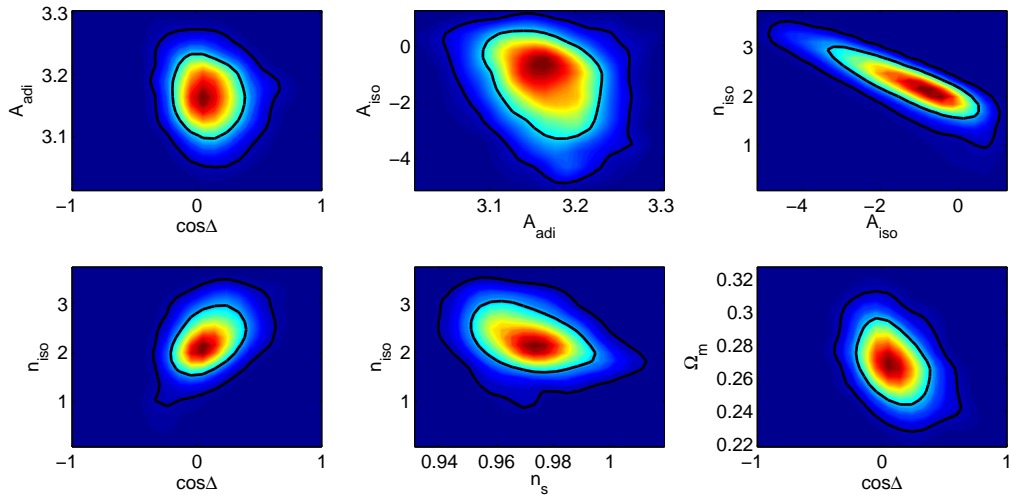


FIG. 4: Two dimensional contours among some cosmological parameters.

correlated adiabatic and isocurvature component raise the peaks of TT spectrum which can be compensated by lower Ω_m . A strongly negative correlation between n_s^{iso} and A_s^{iso} is shown in the right upper panel of Fig. 4.

B. Information on reduced distance parameters

TABLE III: Median 1σ constraints on WMAP normalization priors using full WMAP7 data for different initial perturbations.

		R	l_A	r_s	z_*
WMAP only	Adiabatic	$1.721^{+0.018}_{-0.019}$	302.3 ± 0.7	146.7 ± 1.5	1091.1 ± 0.9
	Mixed	$1.701^{+0.027}_{-0.028}$	$301.5^{+1.7}_{-1.6}$	147.3 ± 1.9	1089.8 ± 1.4
Full data	Adiabatic	1.729 ± 0.010	301.8 ± 0.6	145.7 ± 0.9	1091.3 ± 0.6
	Mixed	$1.700^{+0.026}_{-0.025}$	300.1 ± 1.3	146.4 ± 1.5	1090.4 ± 1.0

The WMAP normalization priors given by WMAP group include the “shift parameter” R , the “acoustic scale” l_A and the photon decoupling epoch z_* . R and l_A correspond to the ratio of angular diameter distance to the decoupling era over Hubble horizon and sound horizon at decoupling respectively, given by

$$R(z_*) = \sqrt{\Omega_m H_0^2 r(z_*)}, \quad (13)$$

$$l_A(z_*) = \pi \chi(z_*) / r_s(z_*), \quad (14)$$

where $r(z_*)$ and $r_s(z_*)$ denote the comoving distance to z_* and comoving sound horizon at z_* respectively. The decoupling epoch z_* is given by [53]

$$z_* = 1048[1 + 0.00124(\Omega_b h^2)^{-0.738}][1 + g_1(\Omega_m h^2)^{g_2}], \quad (15)$$

where

$$g_1 = \frac{0.0783(\Omega_b h^2)^{-0.238}}{1 + 39.5(\Omega_b h^2)^{0.763}}, \quad g_2 = \frac{0.560}{1 + 21.1(\Omega_b h^2)^{1.81}}. \quad (16)$$

The WMAP normalization priors encode in part of the CMB information and can be used to constrain cosmological parameters to some extent. They are derived parameters from the CMB power spectra based on the fiducial cosmological model. Thus, they are model dependent [47, 54]. By using the WMAP7 data only, in Fig. 5 we show the one-dimensional probability distributions of the WAMP normalization priors in two different initial perturbation conditions. The red solid lines are given by pure adiabatic initial perturbations, while the black dash-dot lines are with the mixed case. We find the obvious difference in the probability distributions of R , l_A , and z_* . As we know, the WMAP normalization priors mainly include the information on the oscillatory structures of the CMB power spectrum. As shown in Fig.1, the TT power spectrum can be modified by the CDM isocurvature perturbations, namely the locations and the height of the peaks are modified when taking into account the contributions of CDM isocurvature perturbations. And these effects can lead to the difference of the mean values and errors of WMAP normalization priors.

In table III, we list 1σ constraints on WMAP normalization priors from the full WMAP7 data for different initial conditions. One can see that, by taking into account the contribution from the initial CDM isocurvature modes, constraints of the WMAP normalization priors are obviously changed. The mean values of R is changed about 1σ when comparing with the pure adiabatic case, while for l_A and z_* , the changes are about 1σ and 1.4σ , respectively.

Furthermore, we also provide the 1σ constraints on R , l_A , z_* and r_s using the combined data sample of WMAP7, ACBAR, CBI, Boomerang, as well as SDSS LRG and SN Ia in table III. As we expect, combining the data of SN and LSS can help in constraining the other background cosmological parameters and shrink error bars of R , l_A , z_* and r_s significantly. When considering the CDM isocurvature mode perturbation, we find the differences between the constraints from pure adiabatic perturbation and mixture of adiabatic and isocurvature perturbations are improved obviously. In this case, the difference of the mean values of R , l_A , z_* and r_s become 2.9σ , 2.8σ , 1.5σ and 0.7σ , respectively.

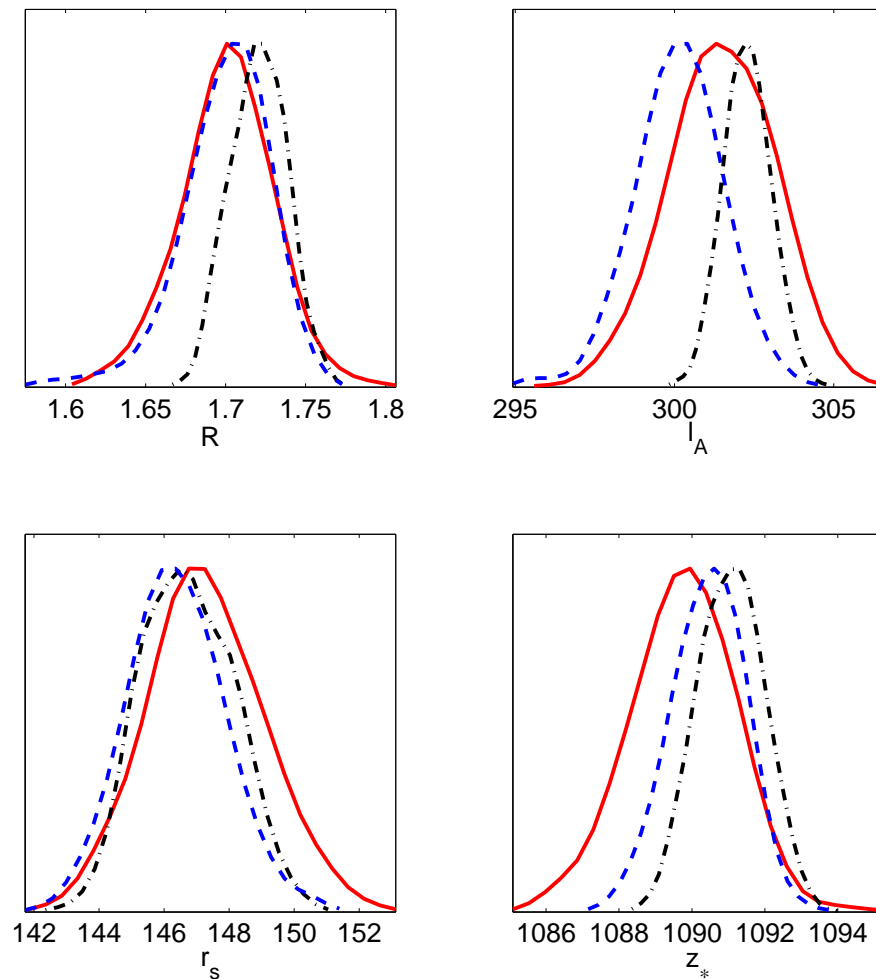


FIG. 5: One dimensional posterior distributions of l_A , R and z_* with WMAP7 data, the red solid lines are given by the mixed initial perturbations, while the black dash lines are from pure adiabatic perturbations.

V. SUMMARY

In this paper, we study the constraints on mixed adiabatic and isocurvature modes of cosmological perturbations. Using the current observational data, such as WMAP7 CMB power spectrum, matter power spectrum of SDSS data released seven LRG data and SNIa “union2” sample, we find an adiabatic initial condition with the presence of certain isocurvature modes can explain the experiments better than a pure adiabatic initial condition. Moreover, we obtained more stringent constraints on the parameters of cosmological perturbations by virtue of the improvement of accuracy of observational data in recent years. Our result shows that the spectral index of isocurvature perturbation has a very blue tilt. This quantity may lead to either enhancement or depression of power spectrum on small scales, which depends on the correlation angle of isocurvature and adiabatic modes.

Given the WMAP normalization priors are widely used in performing testing of cosmological models, we provide the comparison on constraints of R , l_A and z_* from different initial conditions. Since WMAP normalization priors are derived parameters from the CMB power spectra, the constraints are changed obviously when the isocurvature mode modifies of the shape of the peaks and troughs in CMB power spectra.

As an end, we would like to mention that, from the point of view of information criteria, detailed constraints on cosmological parameters depend on the set of parameters of the model which is compared with observational data[55]. The simplest model with purely adiabatic scale-invariant primordial power spectrum is able to capture the most relevant clues of early universe physics, however, more information deserves to be explored along with the improvement of observational data from forthcoming experiments, we expect the global analysis on both CMB power spectrum and matter power spectrum on small scales will be crucial to constrain the isocurvature perturbation.

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